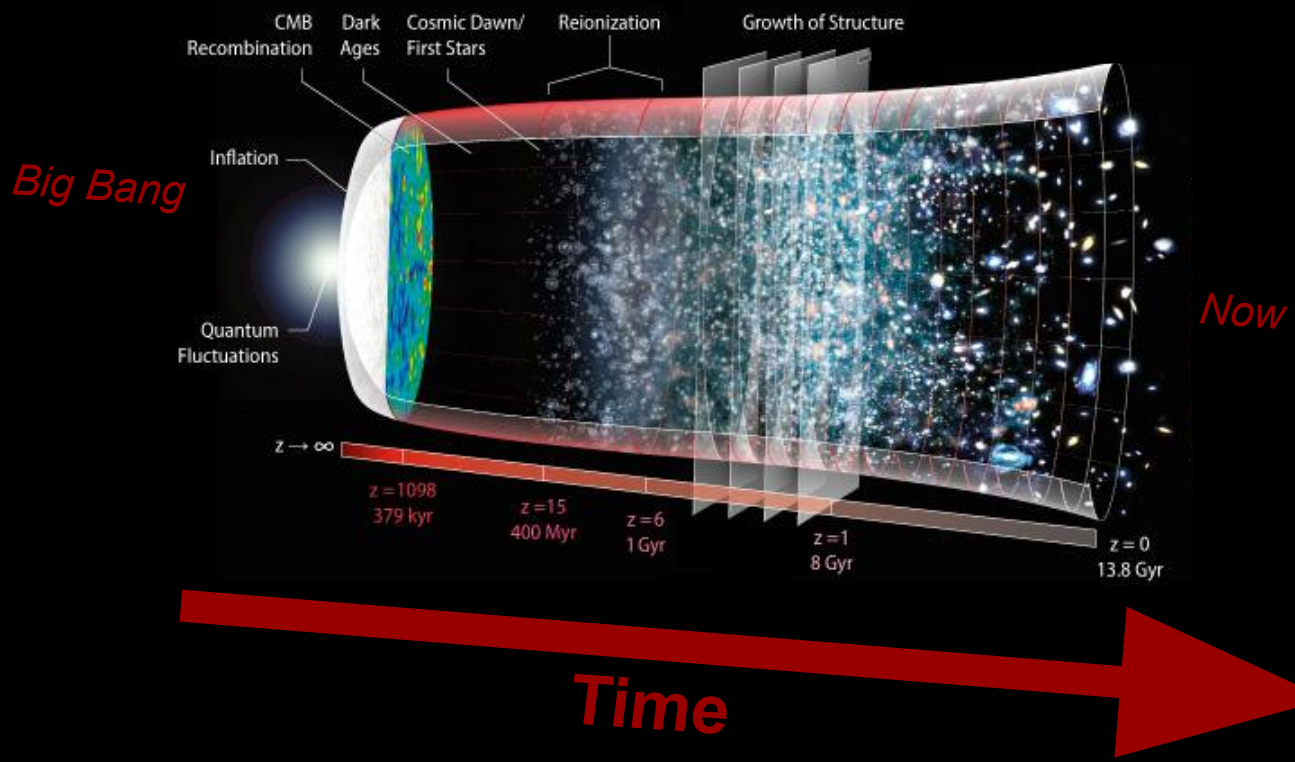
Line Intensity Mapping with mm-wave Spectrometers: Probing the Middle Ages of Cosmic History

Jessica Avva Zebrowski
Einstein Fellow at UChicago
NHFP Symposium
9-18-23

The Observable Universe



Unsolved Mysteries

What is dark energy?

What mechanism drove inflation?

How did the first galaxies and stars form?

Image Credit: NASA / LAMBDA Archive Team

The Observable Universe

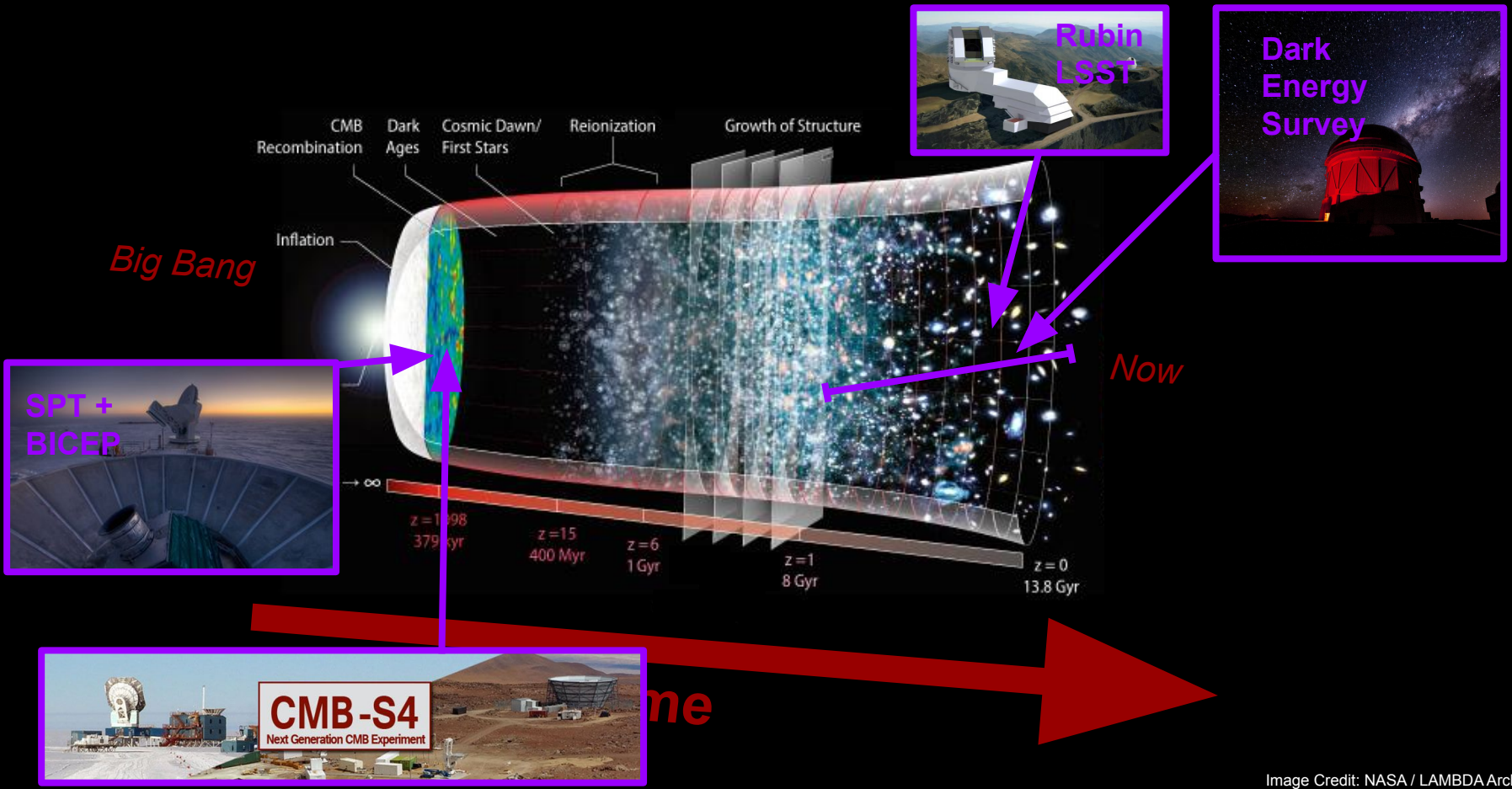


Image Credit: NASA / LAMBDA Archive Team

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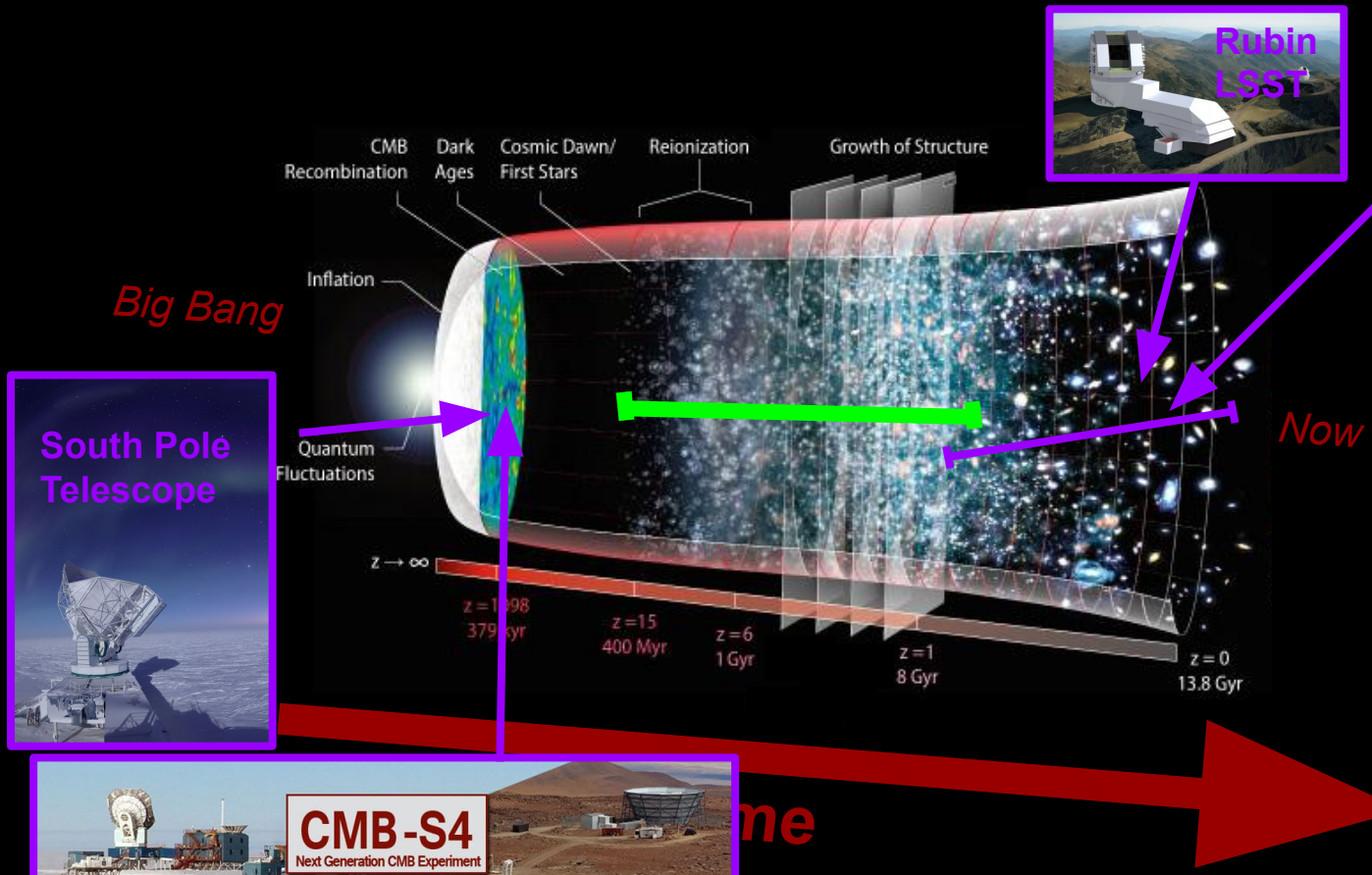
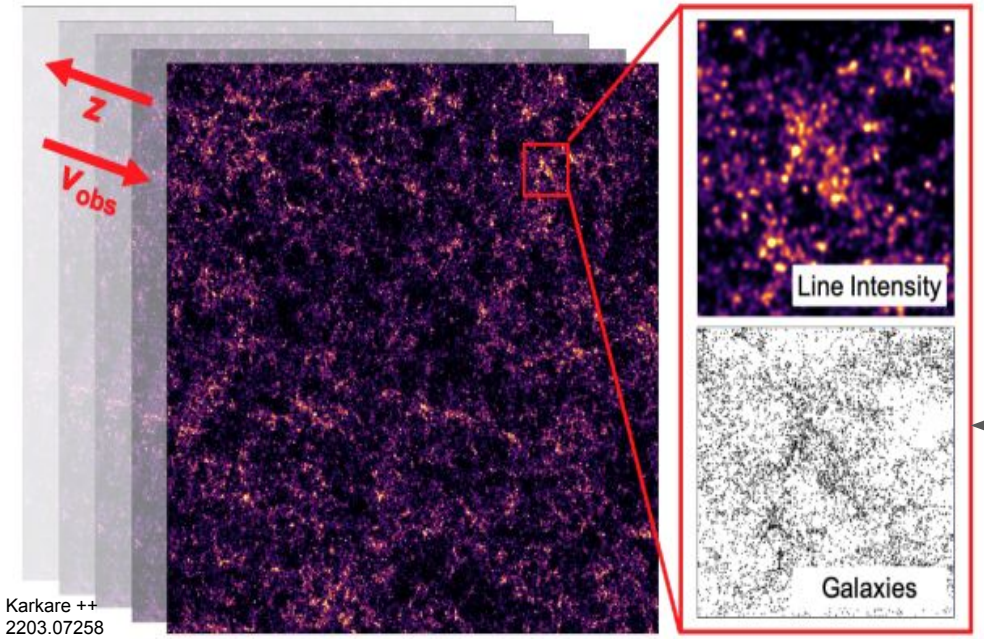


Line Intensity Mapping (LIM)

- Emission from atomic and molecular spectral lines from galaxies (CO, CII, H, etc.)
- Maps the 3D galaxy distribution
- Need *many detectors to measure cosmology*
- Young field! No cosmological constraints measured yet!

Image Credit: NASA / LAMBDA Archive Team

Line Intensity Mapping - The Measurement



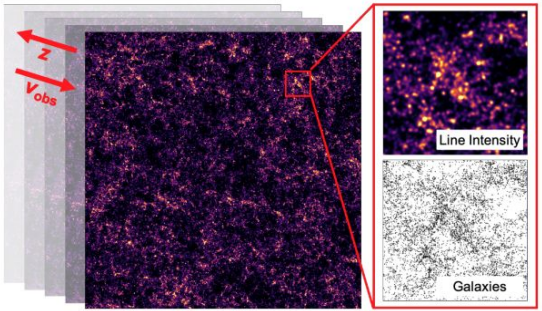
Karkare ++
2203.07258

What you measure
(*low-resolution intensity map of atomic or molecular spectral line emission* x multiple frequencies)

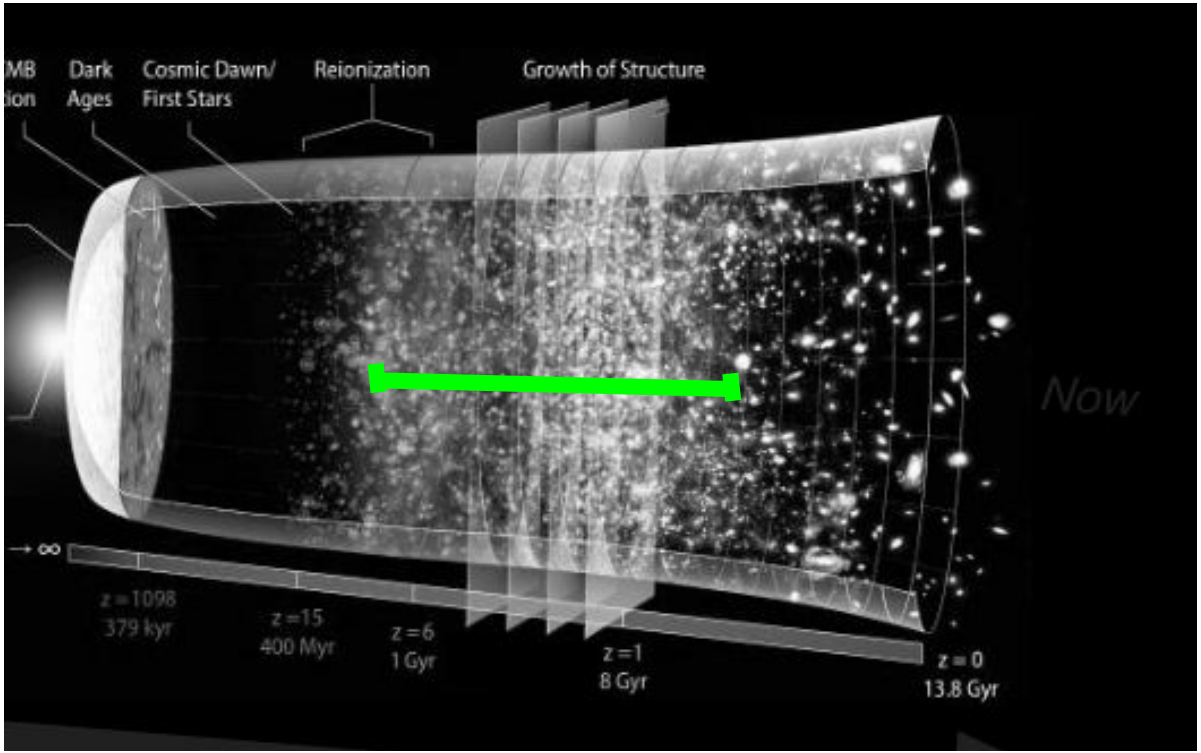
What this traces
(*large-scale structure in the underlying galaxy population/dark matter distribution* as it evolves over time as the spectral line redshifts)

Line Intensity Mapping - The Motivation

From this….



You can constrain…
astrophysics of the high redshift universe



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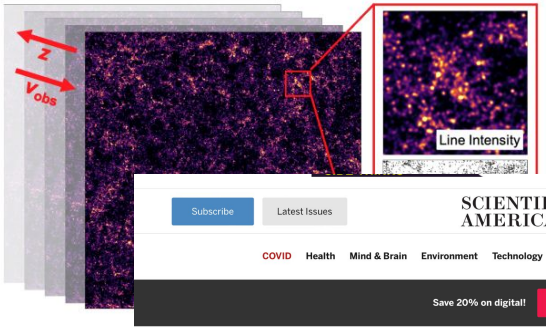

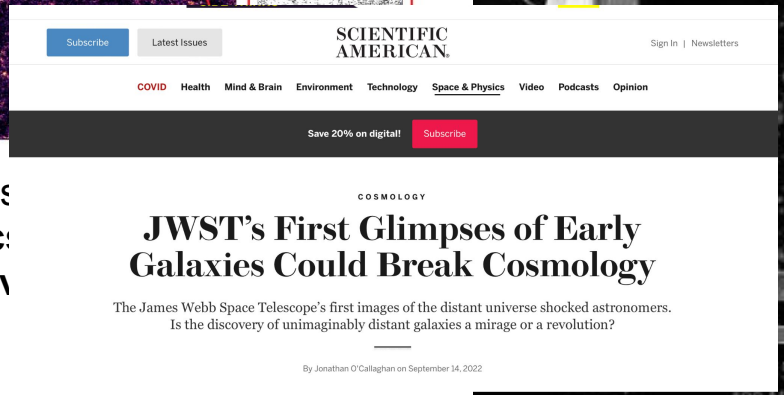
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JWST's First Glimpses of Early Galaxies Could Break Cosmology

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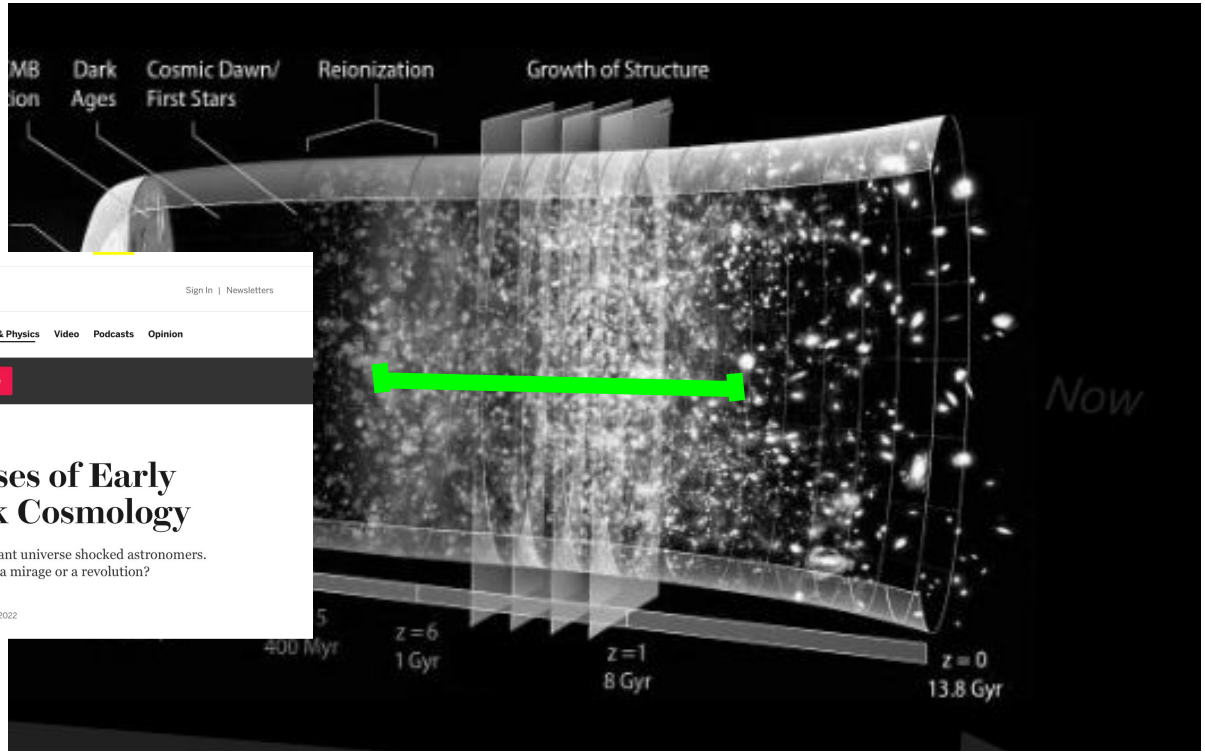
By Jonathan O'Callaghan on September 14, 2022



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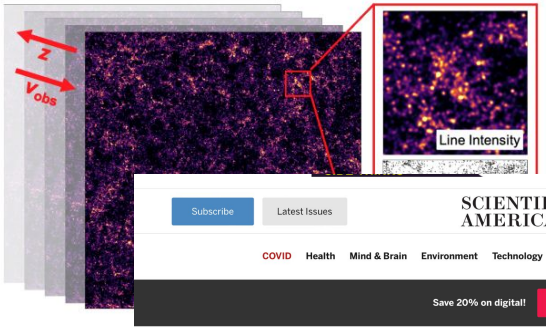

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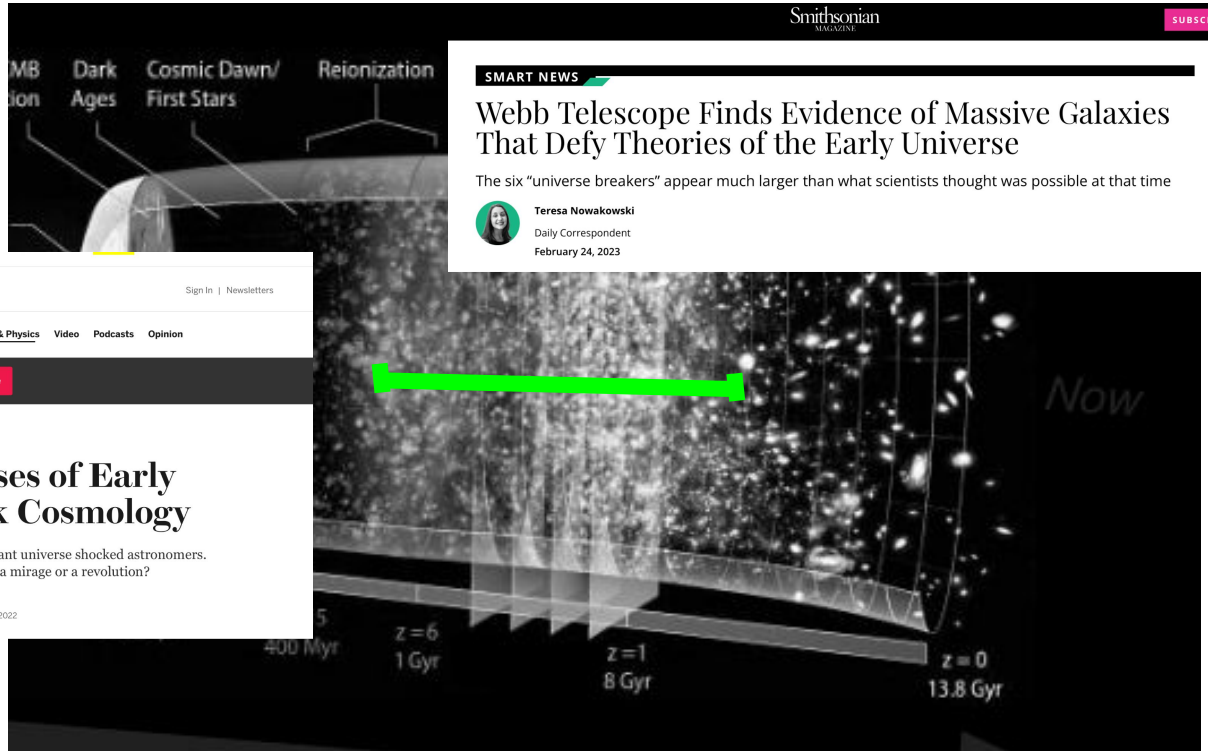

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Webb Telescope Finds Evidence of Massive Galaxies That Defy Theories of the Early Universe

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Teresa Nowakowski
Daily Correspondent
February 24, 2023

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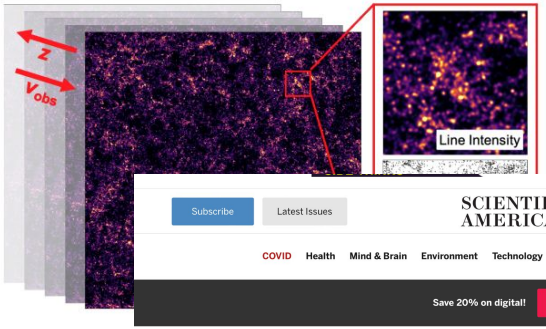

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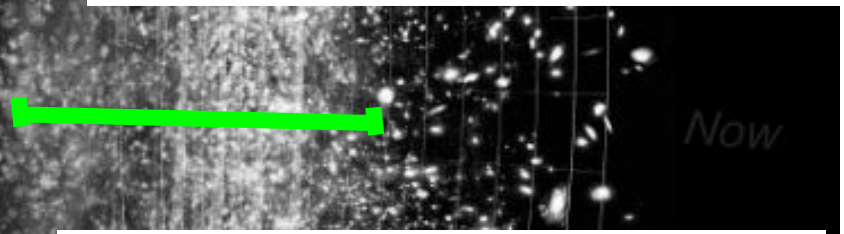

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The James Webb Space Telescope discovers enormous distant galaxies that should not exist

By Tereza Pultarova published February 22, 2023

Giant, mature galaxies seem to have filled the universe shortly after the Big Bang, and astronomers are puzzled.

Comments (45)

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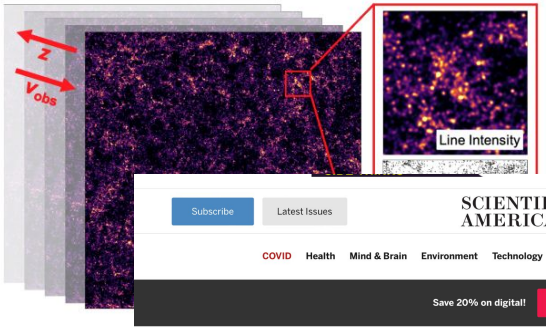

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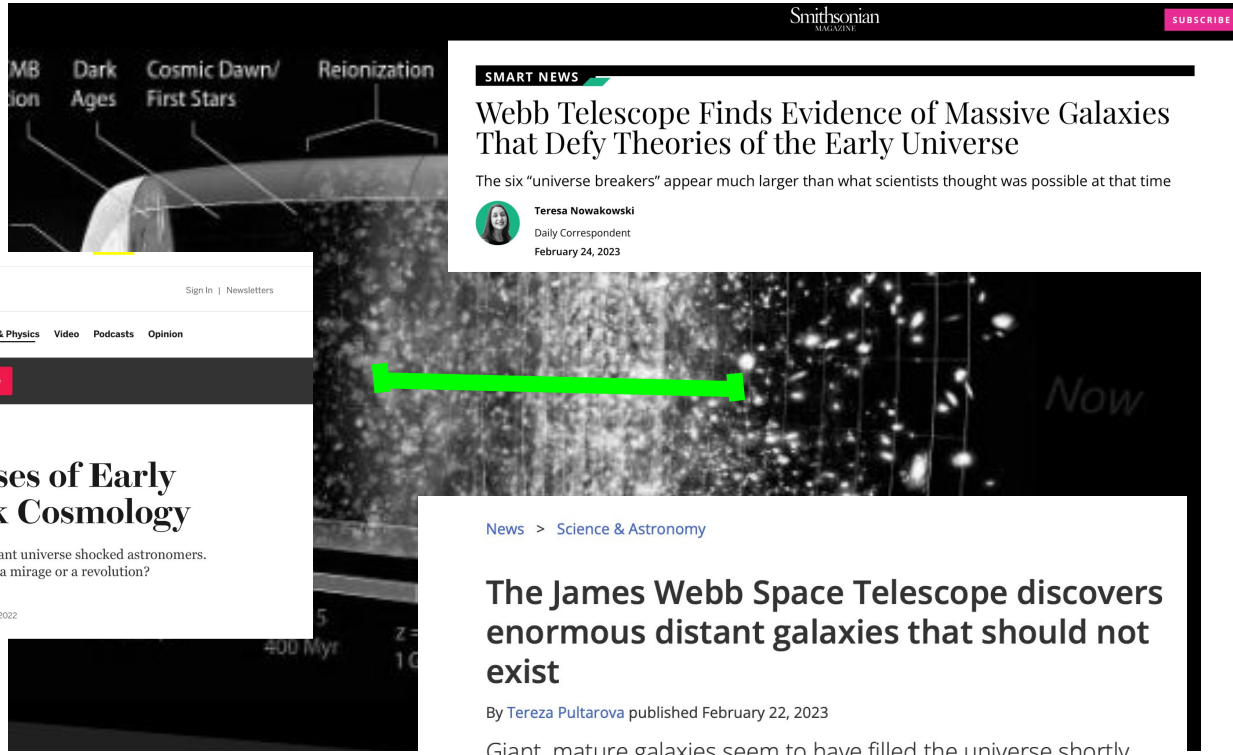

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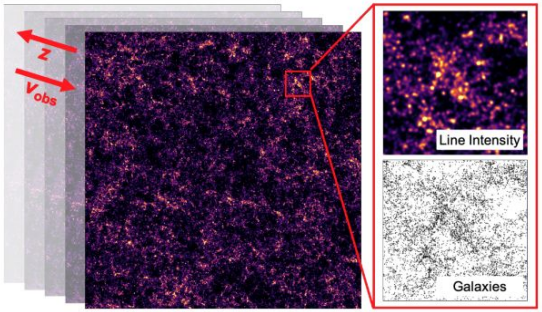
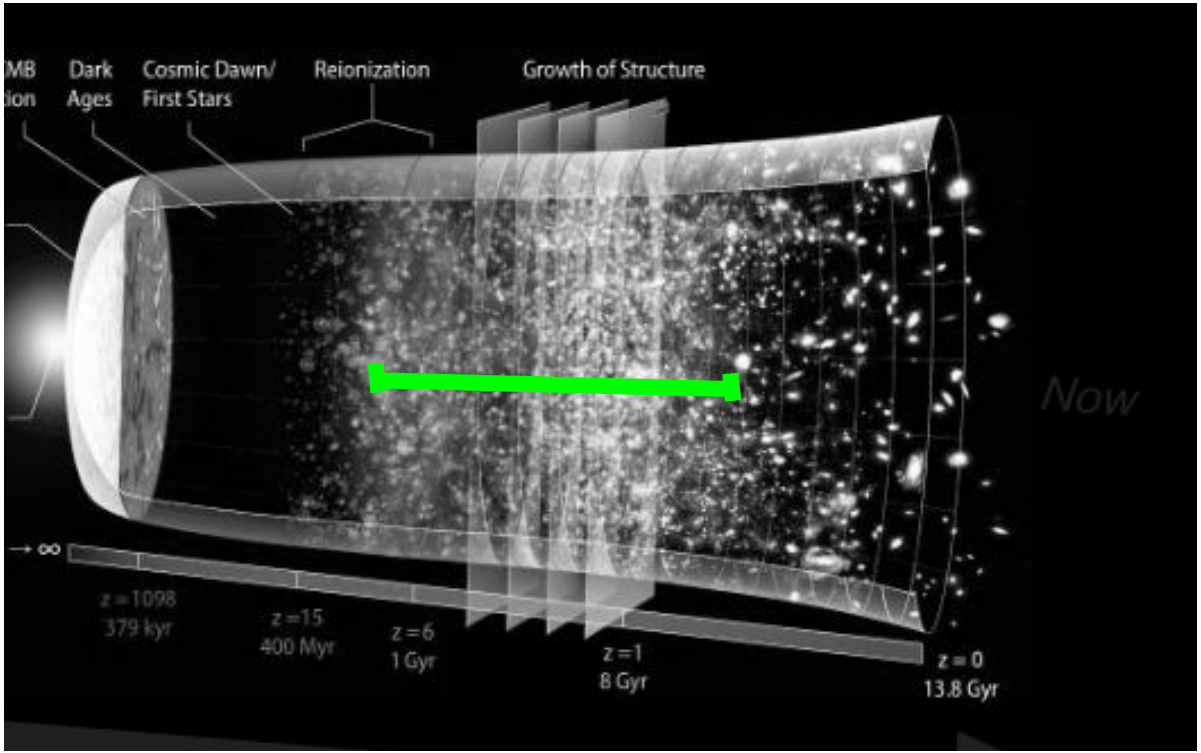


You can constrain…
astrophysics of the high redshift universe

- Integrated map of CO (fuel for star formation), CII (proxy for galaxy luminosity) as a function of redshift
  - Galaxy formation and evolution
  - Star formation history
- Blind search for galaxies



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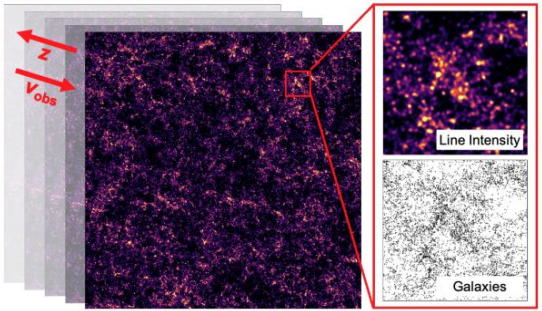
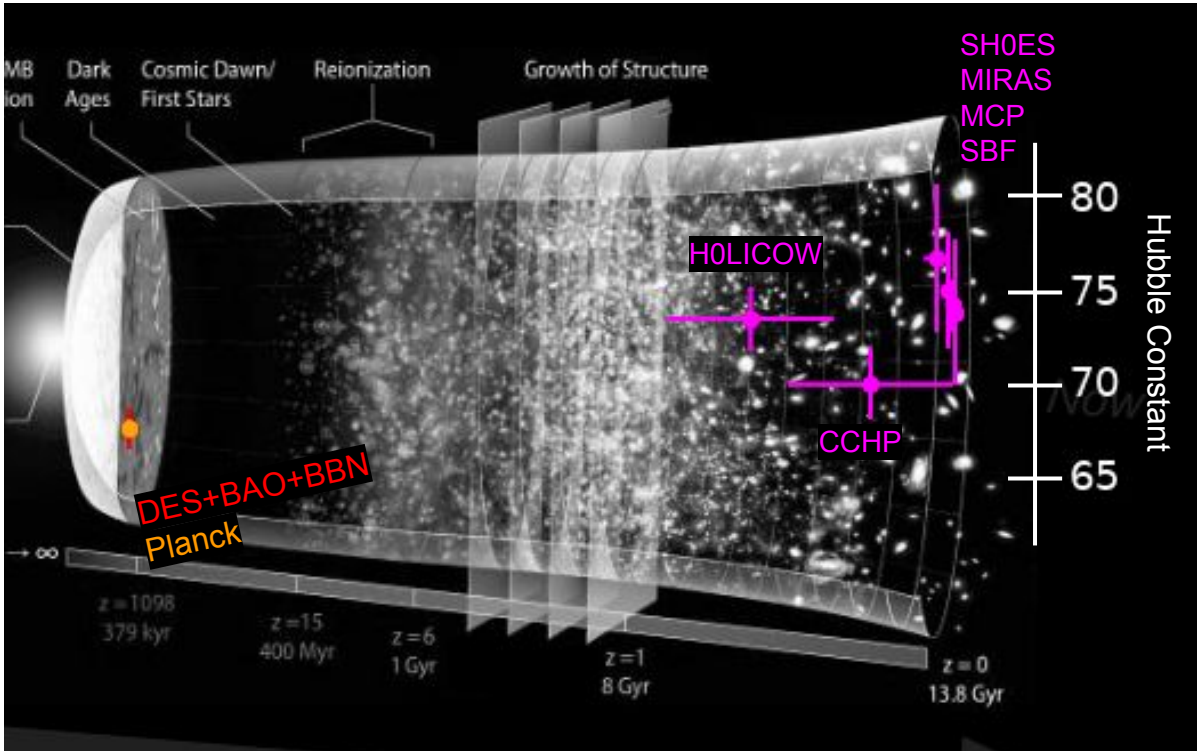


You can constrain… **cosmology**

- Dark Energy



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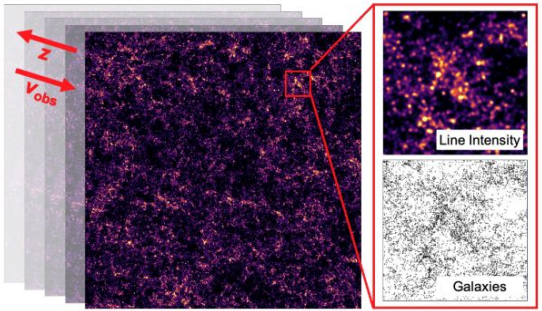
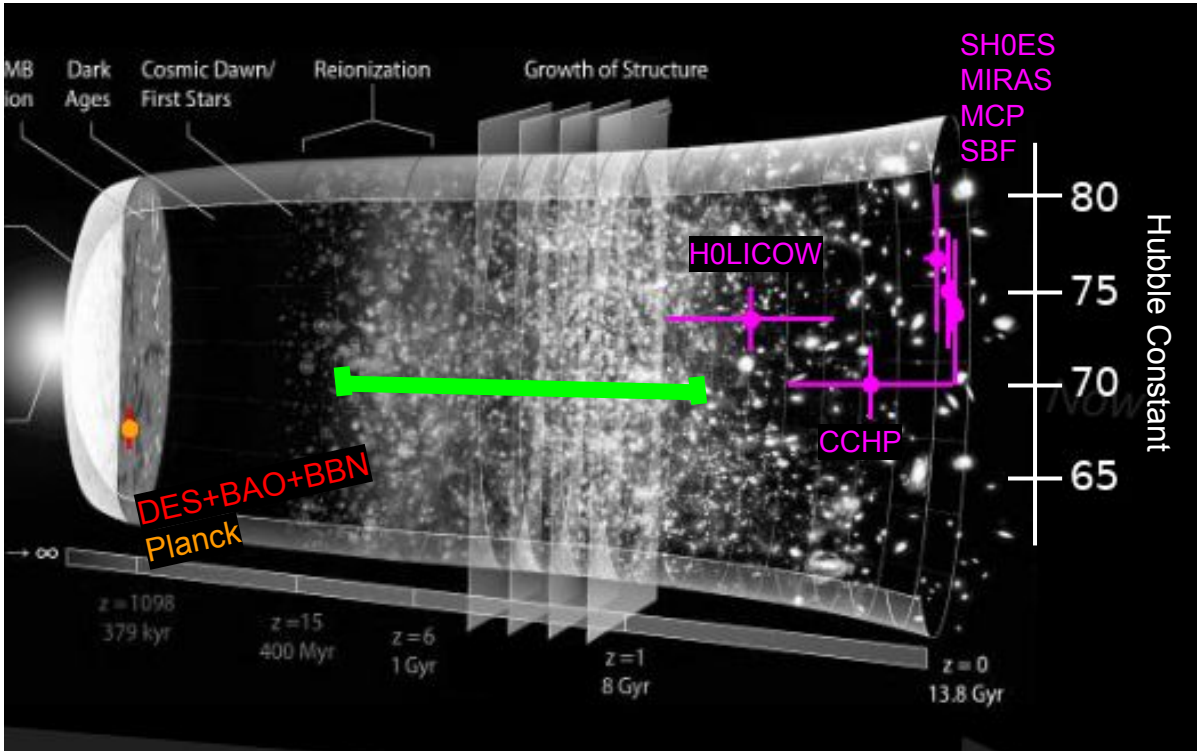


You can constrain… **cosmology**

- Dark Energy
  - Independent measurement at higher redshifts, constrain expansion history



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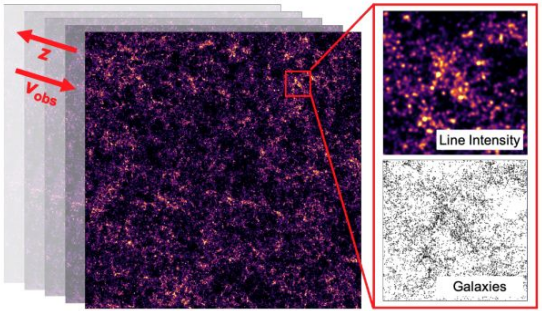
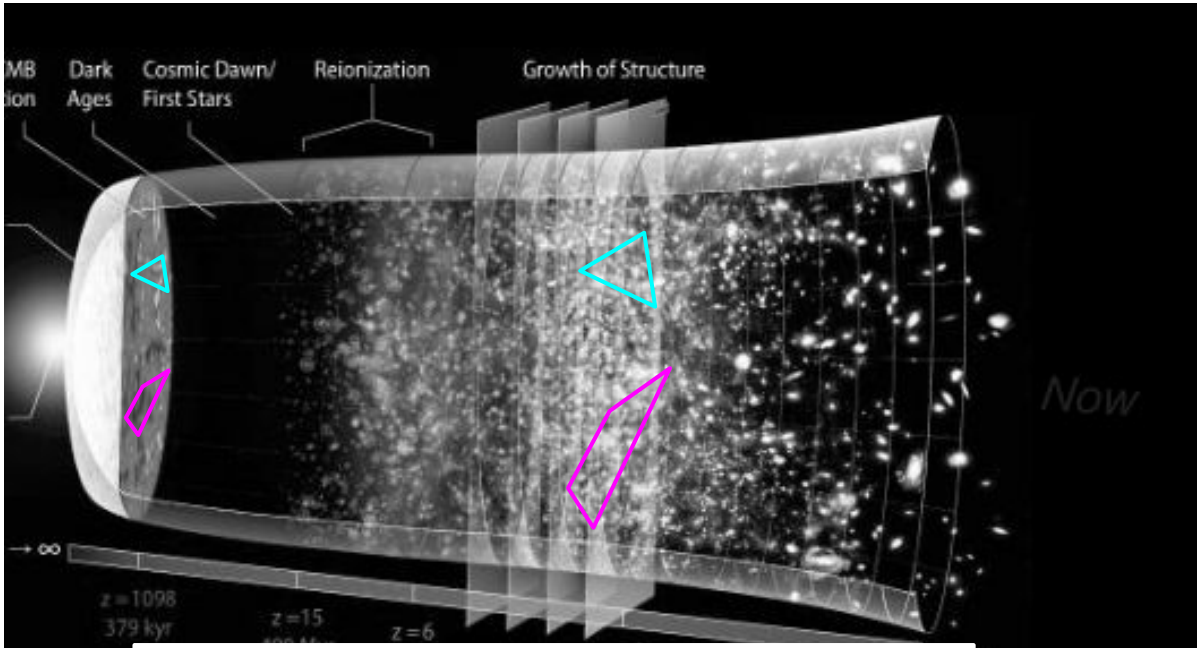


You can constrain… **cosmology**

- Dark Energy
- Inflation
  - Spatial correlations in intensity maps of intermediate redshifts are primordial in nature -- constrain the physics of inflation!



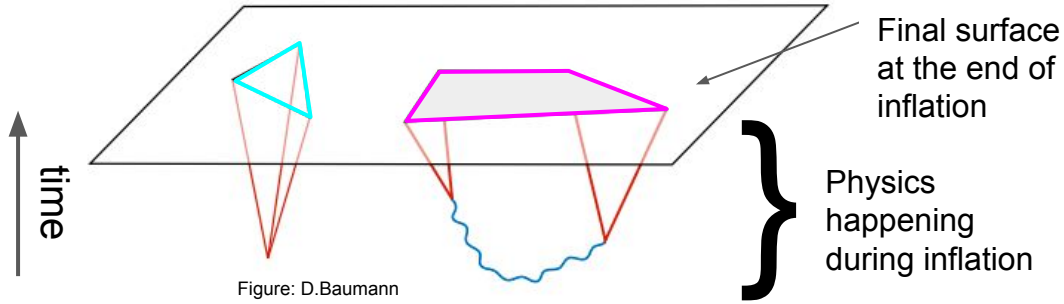
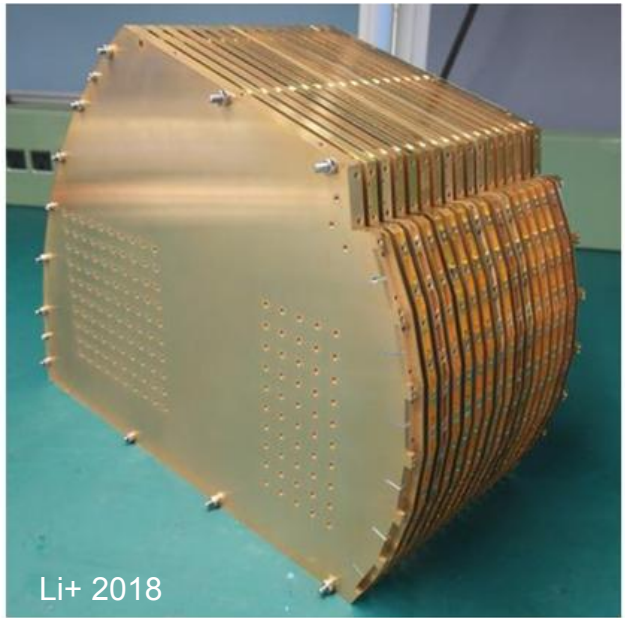


Figure: D.Baumann

Current State of the Art for LIM



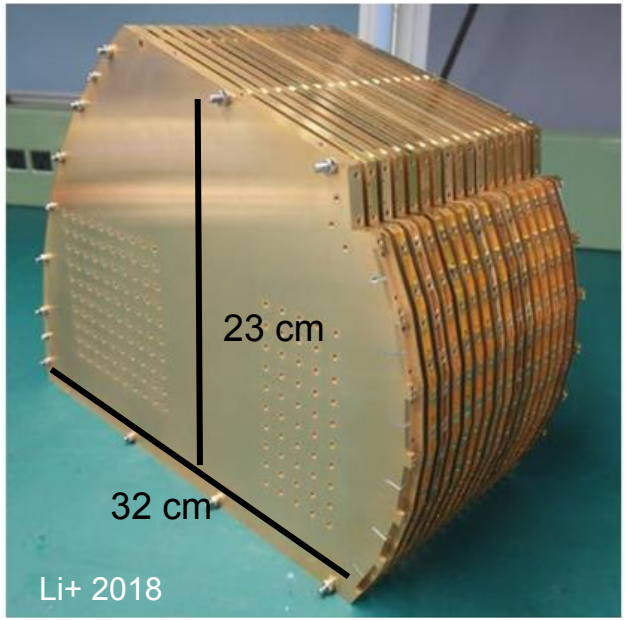
TIME: ~50 diffraction grating spectrometers

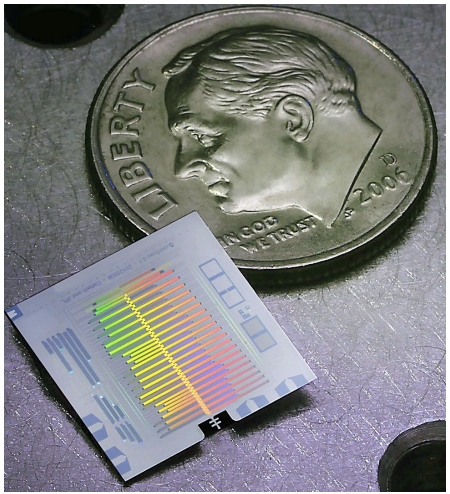
Could reach ~10^5 spectrometer-hours (power spectrum detection, but no serious cosmological constraints)

We need to improve *instantaneous* sensitivity

Current State of the Art for LIM

Single-pixel on-chip spectrometers now being demonstrated on-sky (SuperSpec, DESHIMA)





TIME grating: 32 x 23 x 1 cm
~ 736 cm^3

SuperSpec: 3.6 x 5.7 x 0.05 cm
~ 1 cm^3

SPT-SLIM: SPT Summertime Line Intensity Mapper

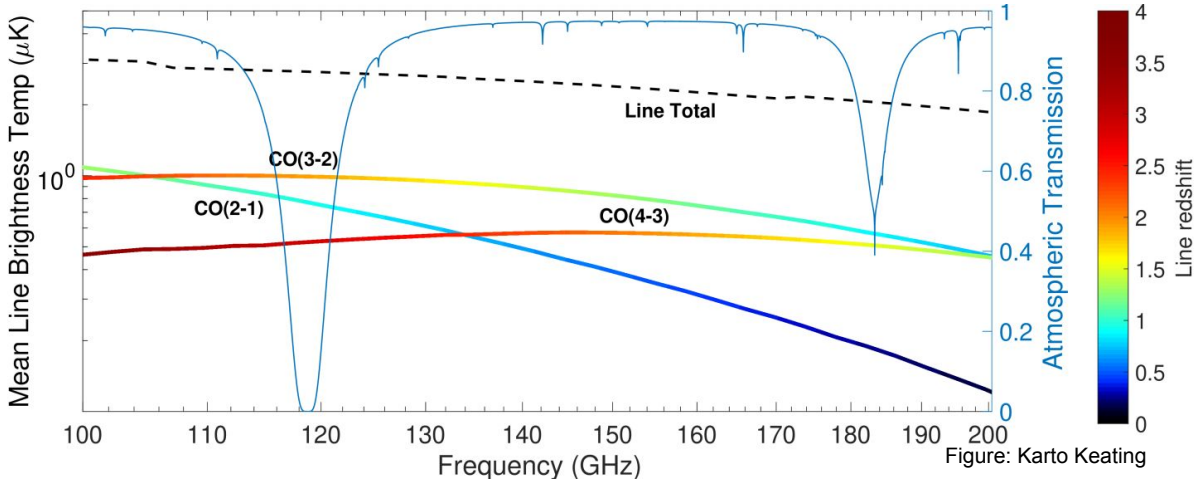
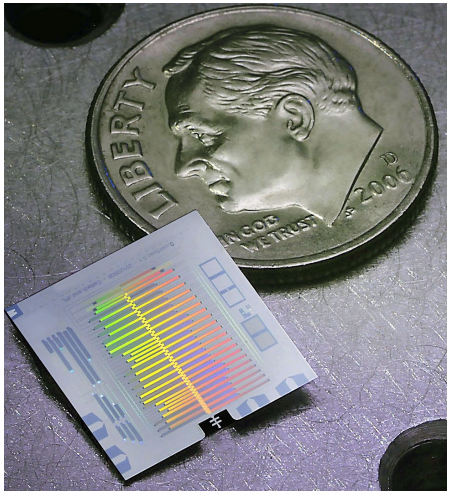


Figure: Karto Keating



- Demonstrate the LIM measurement using on-chip mm-wave spectrometers -- **scalable, a unique technological advantage in the field!**
- Deploy a high-density, 12-pixel dual-polarization focal plane (8400 detectors!)
- 120-180 GHz, sensitive to CO at 0.5 < z < 2
- Deploying Nov 2025 to the South Pole Telescope

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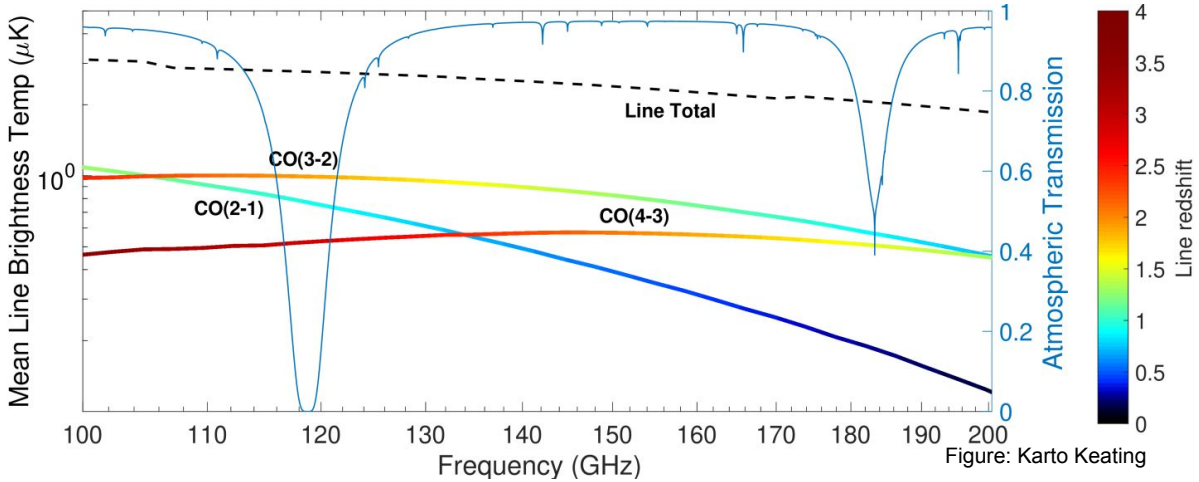

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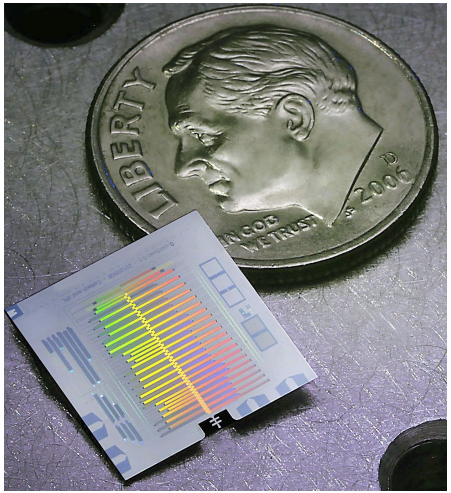

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Powerful proof of this technology and analysis techniques w/ CO detection

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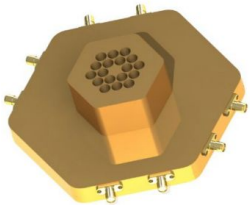


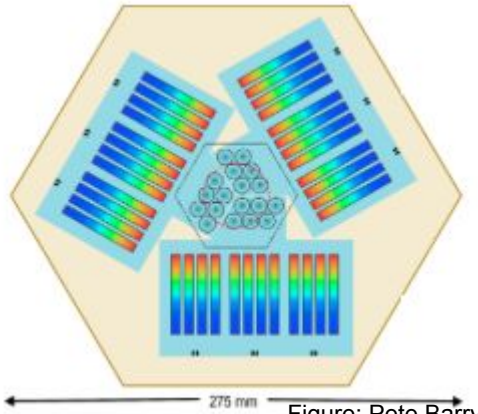
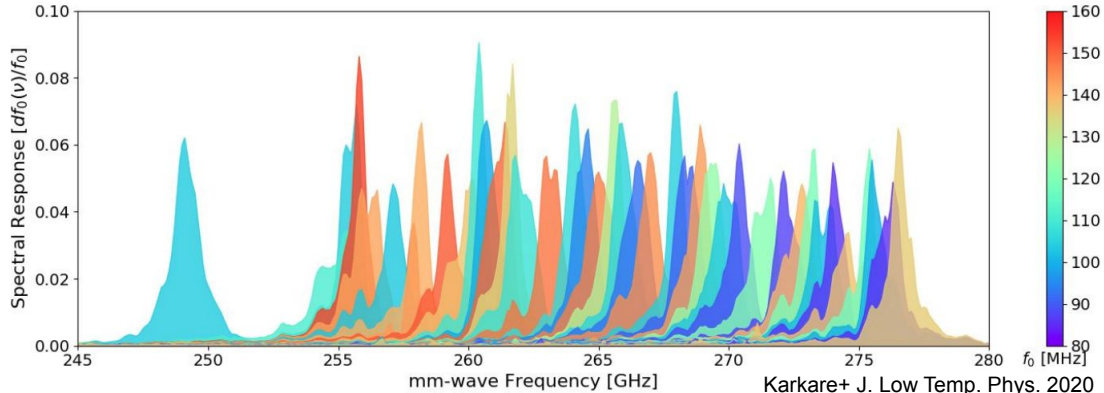


Figure: Pete Barry

- Radiation admitted by conical horns and coupled to spectrometer filterbanks by a planar orthomode transducer (OMT)
- Hexagonal, close-packed array
- 12 spatial pixels sensitive to two polarizations

$$R = \lambda/\Delta\lambda = 300$$



Karkare+ J. Low Temp. Phys. 2020

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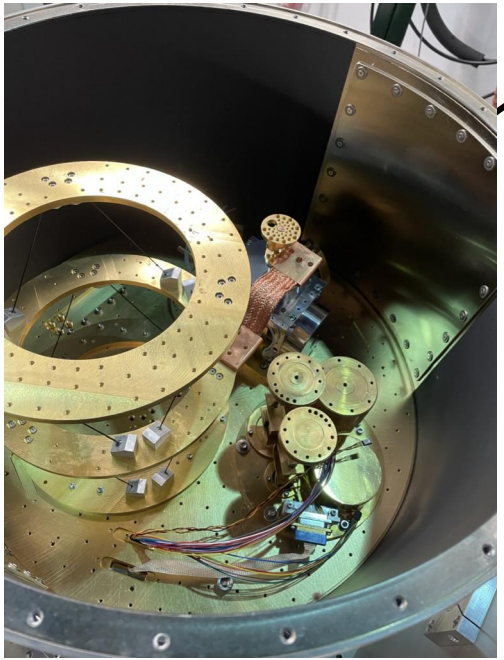

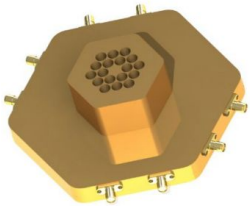

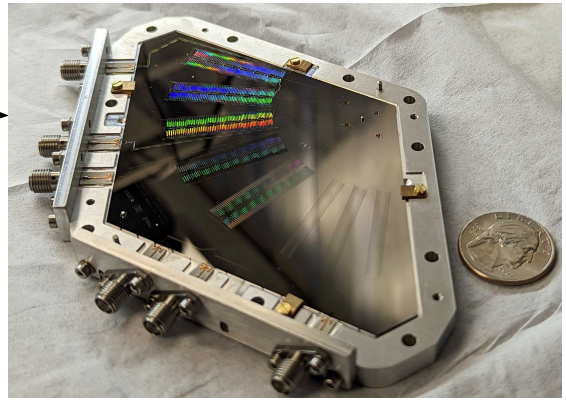

Picture: Kyra Fichman

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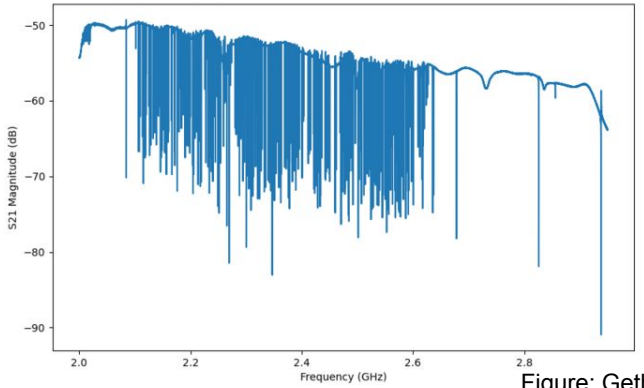

Figure: Gethin Robson

SPT-SLIM Science Projections

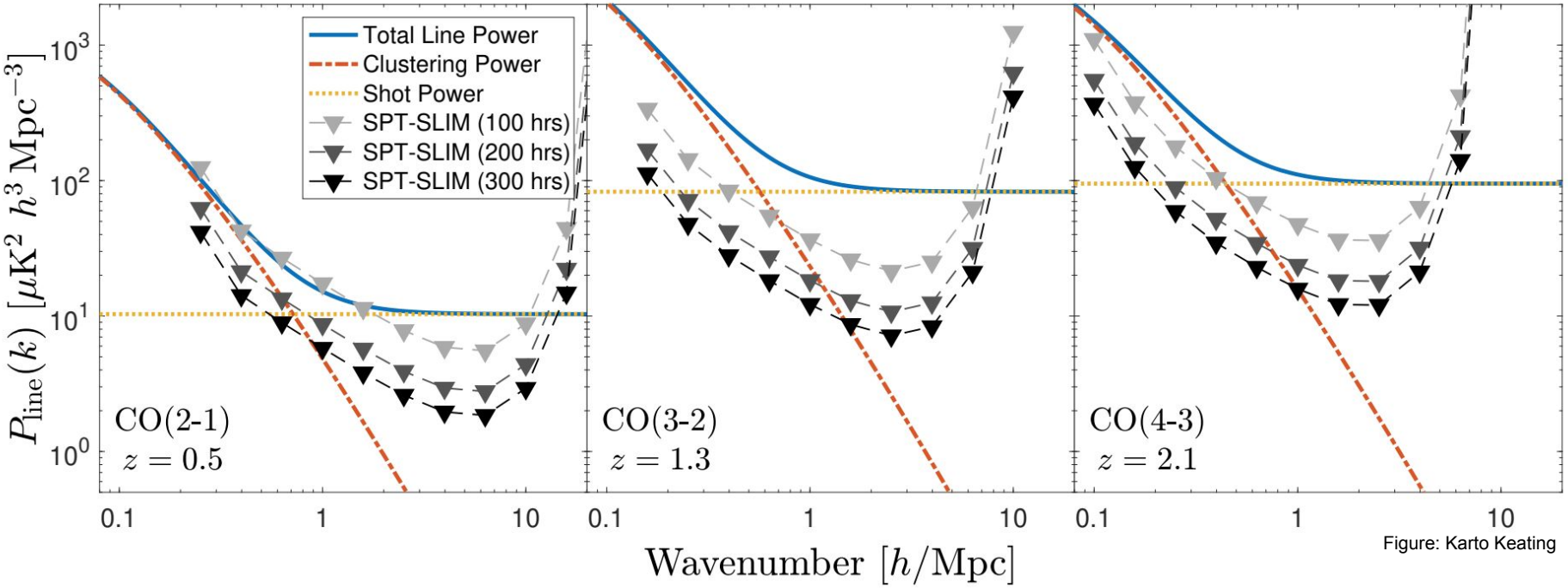

Figure: Karto Keating

- Conservatively expect 50-75% total observing efficiency for ~4 weeks, so >300 hours on-target time is realistic
- Raw sensitivity of SPT-SLIM should be sufficient to detect CO power spectra (0.5 < z < 2) with high significance in a single summer season!

How do we get orders of magnitude improvement for cosmology?

Spec-hrs	Example	Time-scale
10^5	TIME, CCAT-p, SPT-SLIM	2024
10^6	TIME-EXT	2025
10^7	SPT-like 1 tube	2028
10^8	SPT-like 7 tubes	2031
10^9	CMB-S4-like 85 tubes	2037

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LIM becomes competitive with galaxy surveys in the ~10^7 spectrometer-hour range

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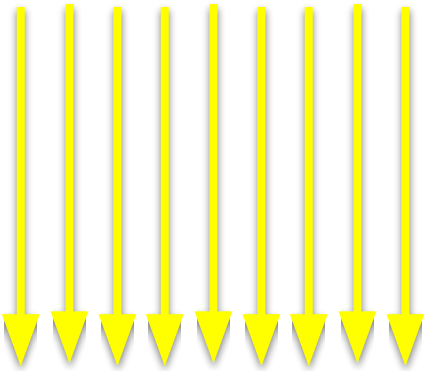
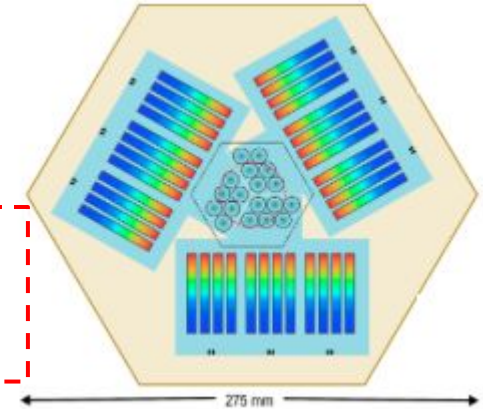
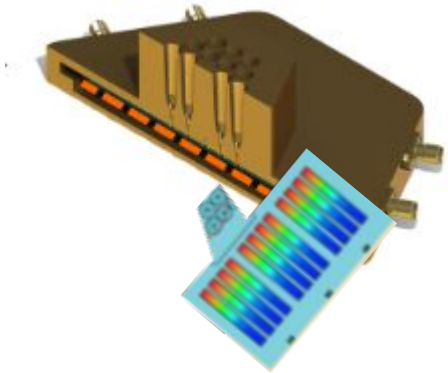
Limiting factor is detector count/focal plane area -- if you want more you need to build a bigger ($$) telescope







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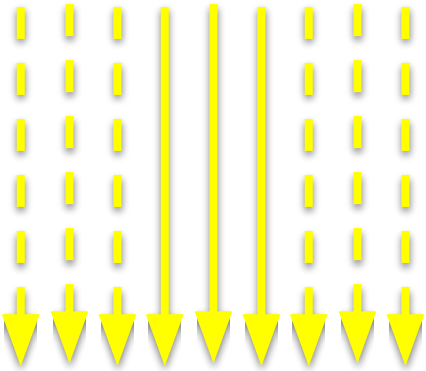
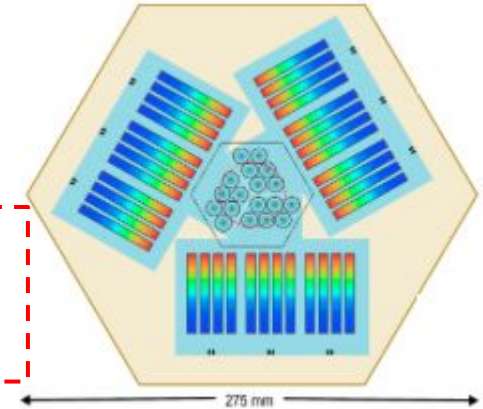
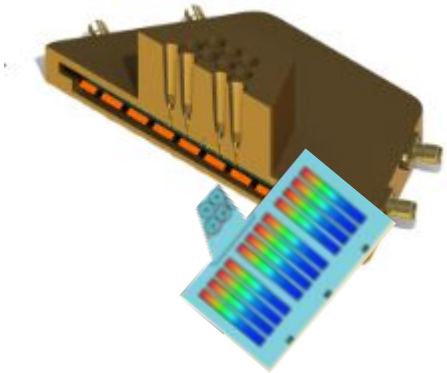
Limiting factor is detector count/focal plane area -- if you want more you need to build a bigger ($$) telescope







LIM becomes competitive with galaxy surveys in the ~10^7 spectrometer-hour range

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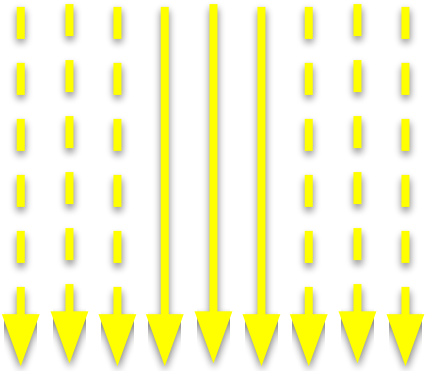

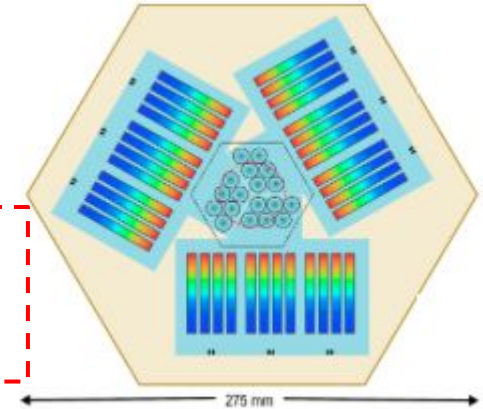

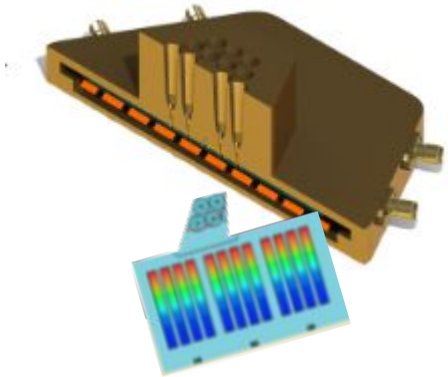

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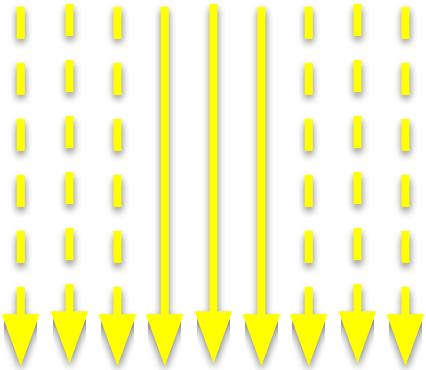

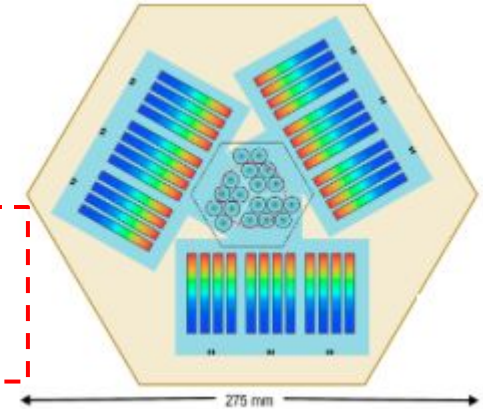

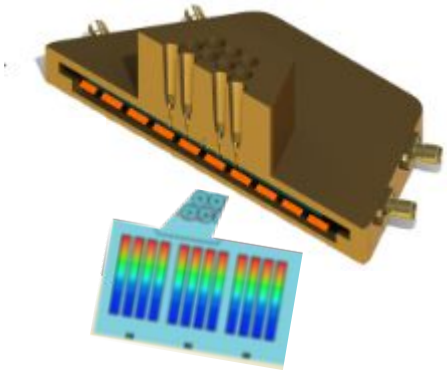

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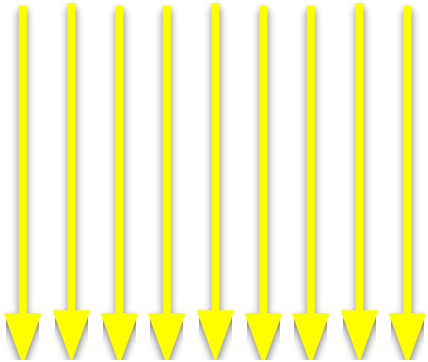

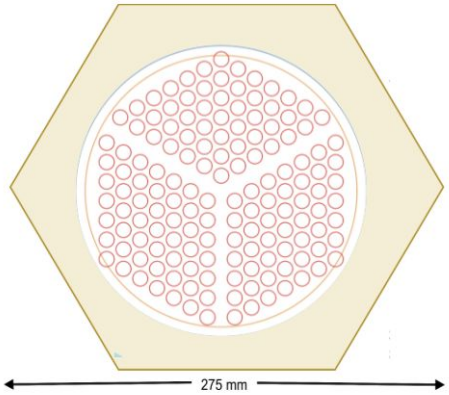

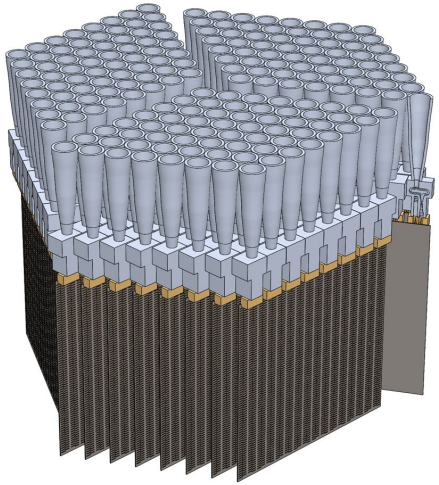

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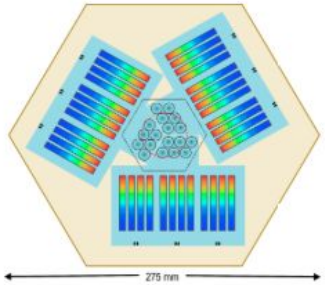
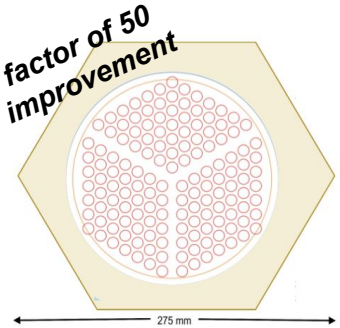
Next Generation of Focal Plane Technology

In collaboration with:
Jeff McMahon
Austin Stover
Sara Simon



12 Spectrometers
120-180 GHz Bandwidth



294 Spectrometers
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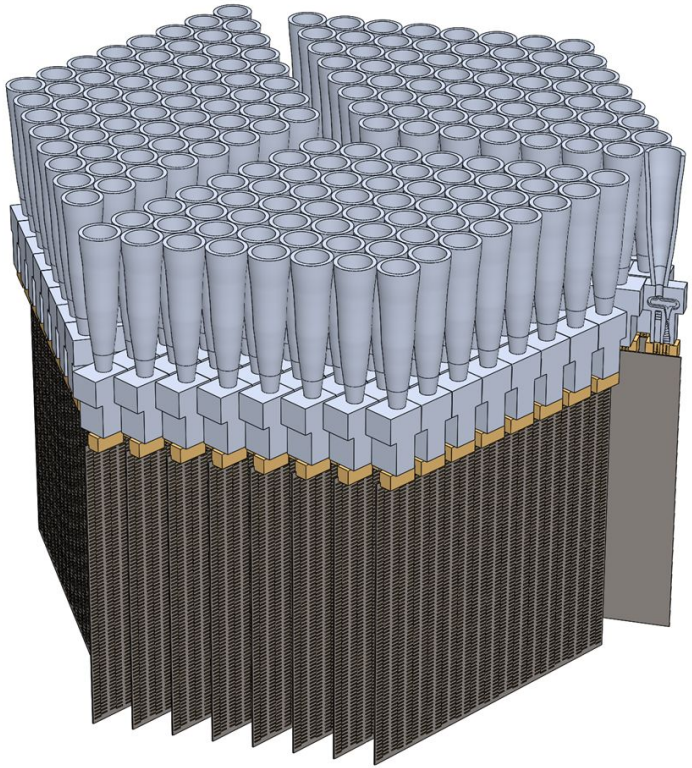

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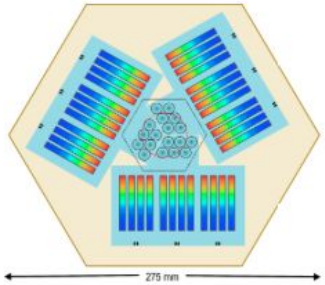

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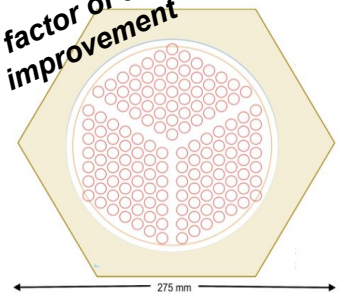

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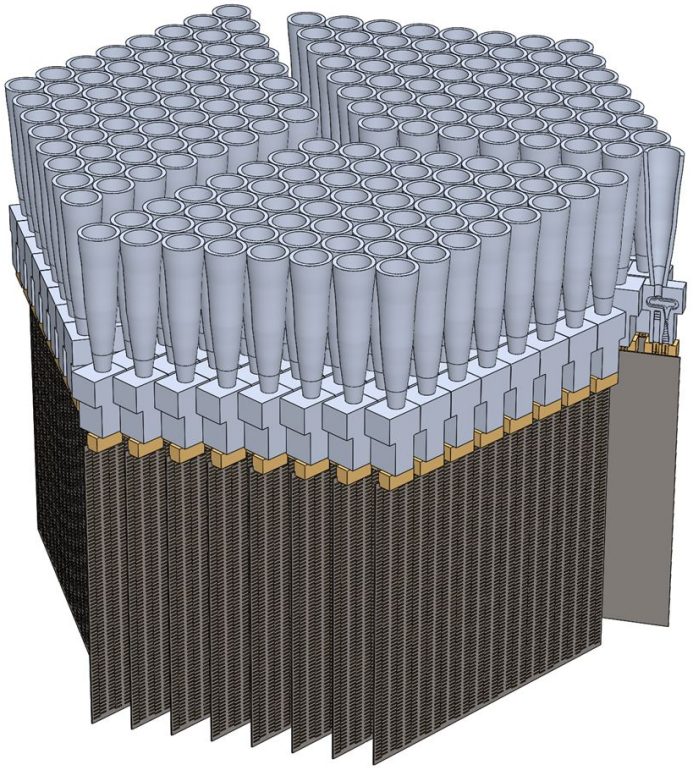

Conical Feedhorns
to couple light

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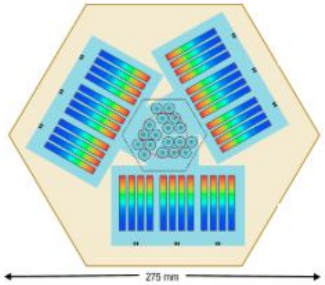

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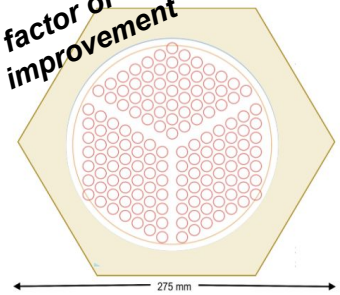

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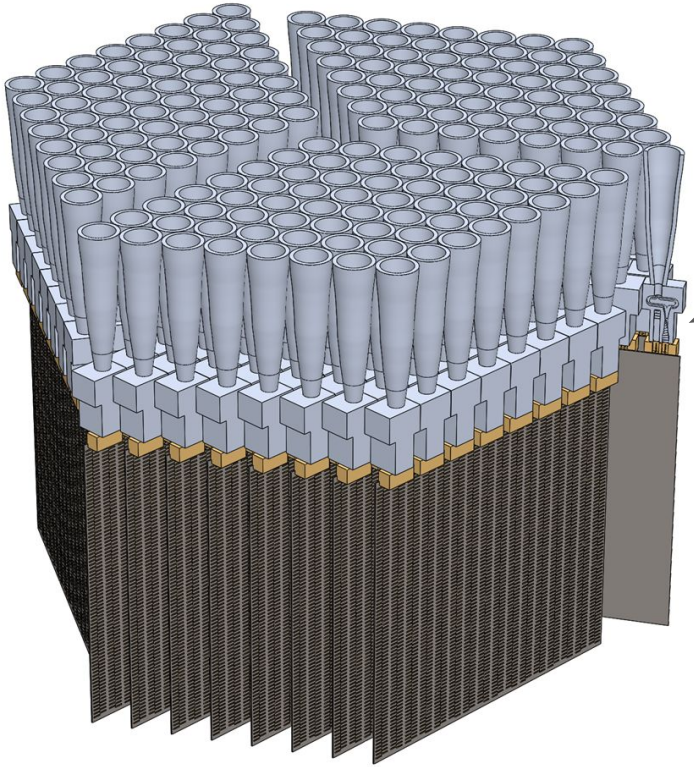
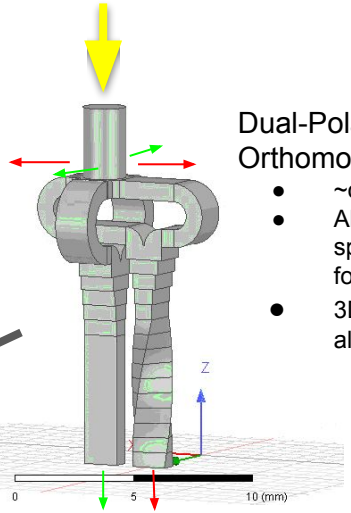
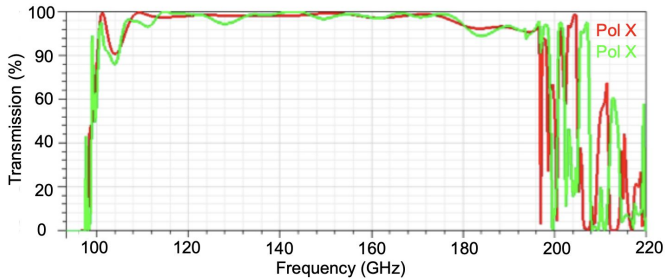




Dual-Polarization Orthomode Transducer:

- ~octave of bandwidth
- Allows for 2x more spectrometers per focal plane area
- 3D print out of aluminum



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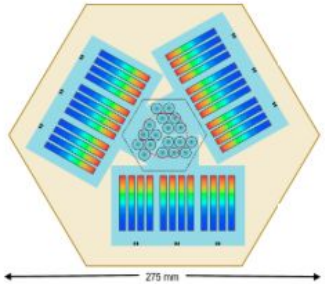

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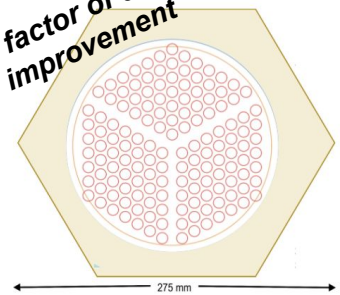

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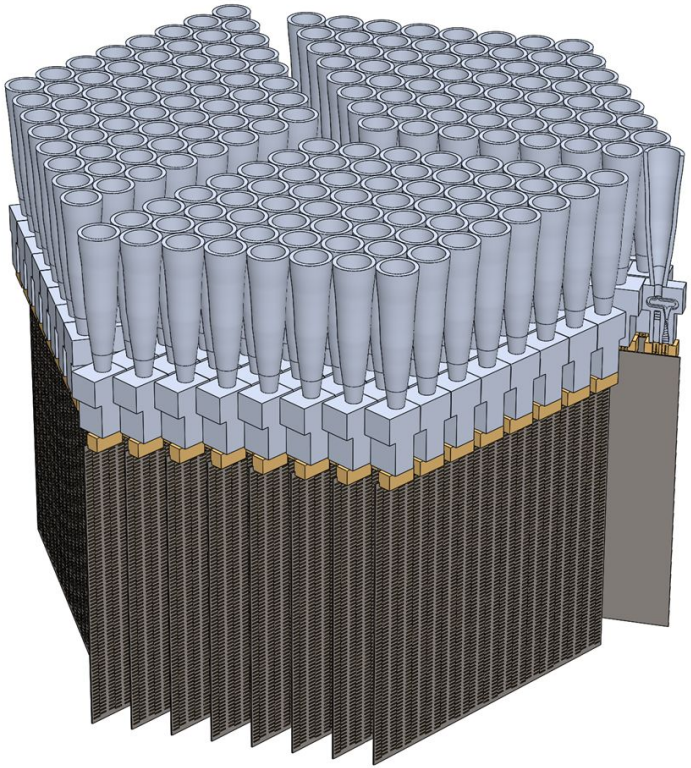
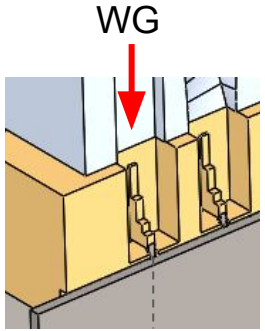
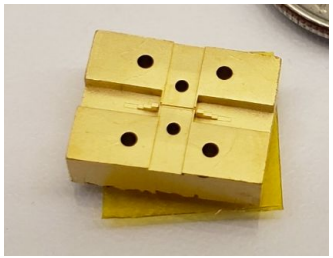


Waveguide (WG) to Co-planar Waveguide (CPW) transition



CPW on spectrometer chip



3D printed ceramic, then gold-plated

Proof of concept- all tolerances in-spec!

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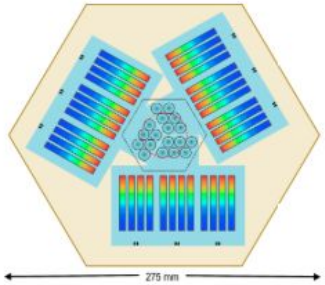

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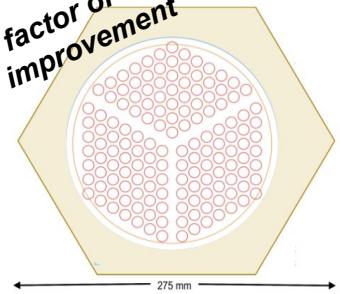
factor of 50 improvement



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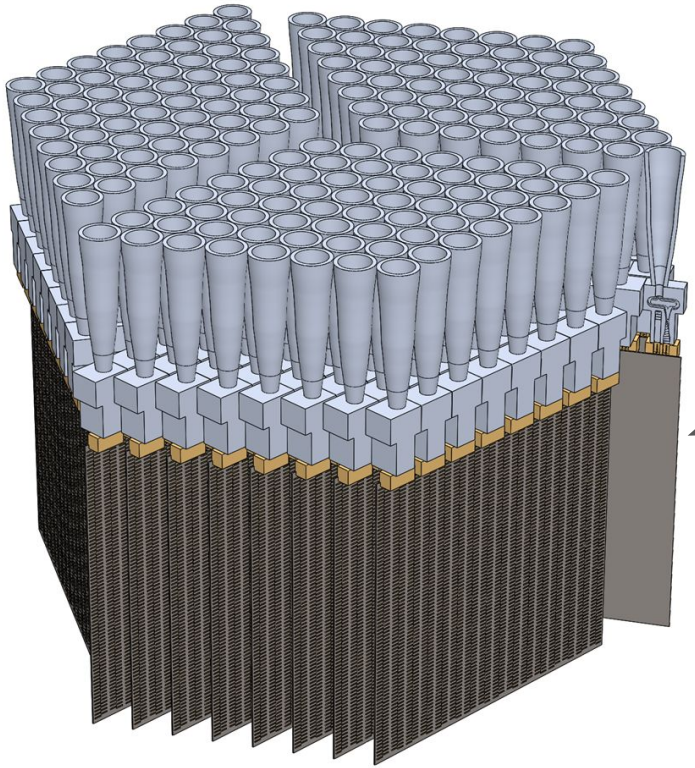
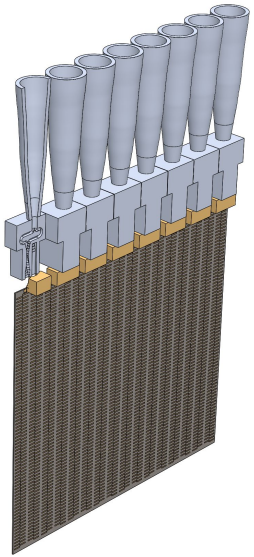


Spectrometer Card

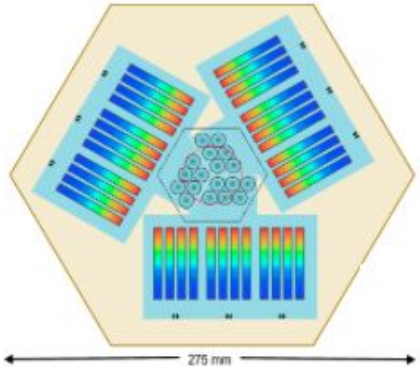
Efficient to fabricate modular system



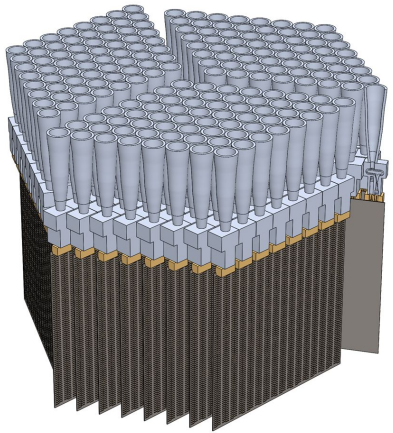
Summary

- Novel technology probes previously sparsely measured parts of cosmic history
- On-chip spectrometer technology + vertical focal plane scalable for increased sensitivity to cosmology
- A detection of the CO power spectrum with SPT-SLIM will demonstrate analysis and hardware techniques for the next-generation of experiments and beyond, and pave the way for cosmological constraints

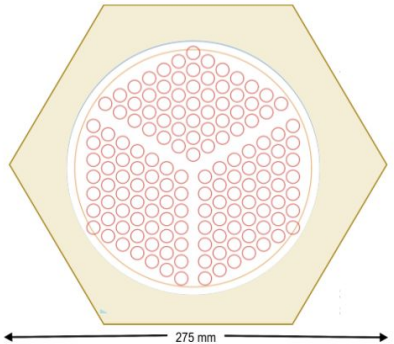
SPT-SLIM



First light winter 2024!



Next-Gen Focal Plane



First test parts fabricated winter 2023!